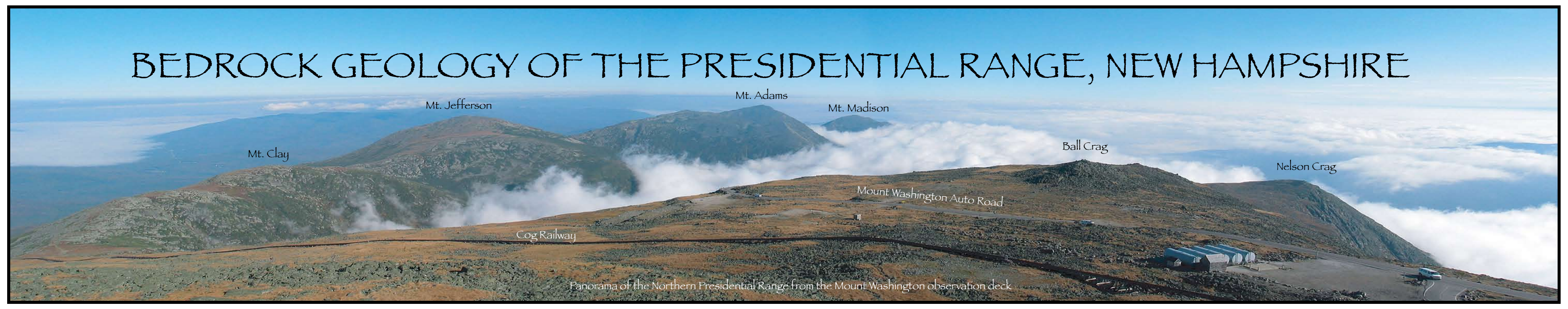
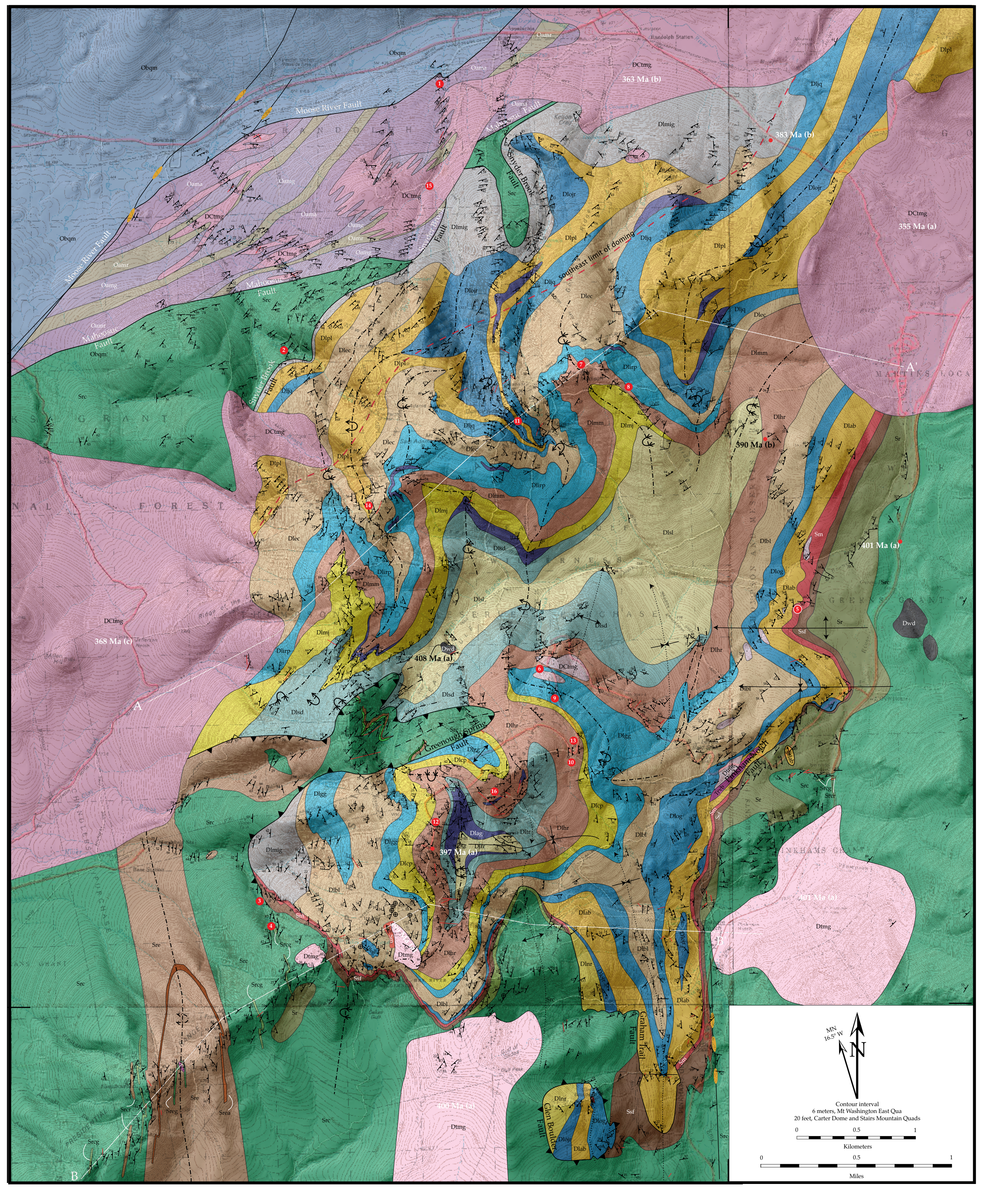
BEDROCK GEOLOGY OF THE PRESIDENTIAL RANGE, NEW HAMPSHIRE



Panorama of the Northern Presidential Range from the Mount Washington observation deck



IGNEOUS ROCKS

TRIASSIC

Trvb Trvb - Triassic (?) vent breccia, predominatley felsic in composition.

LATE DEVONIAN TO EARLY CARBONIFEROUS

DCtmg DCtmg - Two mica granite
A medium- to coarse-grained, light gray to white, two mica granite. The granite is generally not foliated but in places zones of foliation exist. Zones of coarse-grained pegmatitic granite, pegmatite, and fine-grained aplite are also included in this lithology. Principally forms numerous small sills, dikes, veins, and random lenses, to small to map, intruding into gneissic metasedimentary rocks. Also occurs as scattered, small, sill-like, plutons up to 2 kilometers in length. Lenses of well-foliated schist and or gneiss are commonly found within these plutons.

EARLY DEVONIAN

Dtmg Dtmg - Two mica granite
A medium- to coarse-grained, gray to rusty weathering two mica granite. Schlieren and xenoliths are common. In places a complete gradation with adjacent metasedimentary units is observed. Fine-grained aplite and pegmatite are common. Principally forms numerous small concordant plutons many of which are too small to map.

EARLY DEVONIAN

Dwd Dwd - Wamsutta Diorite
A medium-grained, dark gray diorite. Zones of well foliated diorite are common. The one occurrence of this pluton is in the Great Gulf region at Wamsuttta Falls.

METASEDIMENTARY ROCKS

DEVONIAN

Dl - Littleton Formation - general description
The Littleton Formation consists of dark gray schists commonly with interbedded quartzite layers of varying thickness and abundance. The schists are composed of quartz, muscovite, biotite, plagioclase, chlorite, sericite, sillimanite, ilmenite, tourmaline, staurolite, garnet, and trace monazite, and zircon. Andalusite, generally completely pseudomorphed by muscovite, sillimanite, and sericite, is common in the schists forming lumps, approximately 1 to 3 cm in diameter, and elongate aggregates, from 1 to 15 cm in length, with rare relict cores of fresh pink andalusite and/or chiasolite crosses. Foliation in the schists is well developed and is usually parallel to bedding. In F1 fold hinges, bedding and foliation become oblique to each other. The quartzites are fine-grained, light gray, granoblastic and composed of quartz, plagioclase, muscovite, and biotite. Graded beds, reversed in grain size by high grade metamorphism, are common throughout the formation. The descriptions of the Littleton Formation members given below focuses on the variations in bedding style of the schists and quartzites and any other lithologic peculiarities. All contacts between the members of the Littleton are gradational.

Littleton Formation Members. Members in the Northern Presidentials listed first followed
by correlative members found in the Southern Presidential Range

Dlsl Dlfr Dlsl - Spaulding Lake Member - Dlfr - Frog Rock Member
Massive schist with coarse, lumpy pseudoandalusites. Rare quartzite beds up to 10 cm thick, are occasionally found. Poorly bedded with very rare graded beds.

Dlag Dlag - Alpine Garden Member - Massive quartzites commonly 1 to 4 meter in thickness with rare thin, 1 to 8 cm thick schist interbeds, often well graded. Most quartzites show a light rusty brown weathering near the base of the bed. Thickness, 0 to 175 m.

Dlsd Dltr Dlsd - Sphinx Dome Member - Dltr - Tuckerman Ravine Member
Well bedded schist and quartzite, the couplet being approximately 10 - 50 cm in thickness and equally divided between the two lithologies. Well developed, aligned pseudoandalusites and graded beds.

Dlmj Dlcp Dlmj - Mt. Jefferson Member - Dlcp - Cow Pasture Member
Massive schist with coarse, lumpy pseudoandalusites and up to approximately 10% quartzite. Where quartzites are found the beds range between .5 to 1 m in thickness with the quartzites between 10 and 30 cm in thickness. In these places graded bedding is common. Well developed aligned pseudoandalusites are found in the schist.

Dlmm Dlhr Dlmm - Mt. Madison Member - Dlhr - Huntington Ravine Member
A rhythmically bedded schist and quartzite, each couplet remarkably uniform in thickness, approximately 3 - 10 cm. Rare garnet coticules are found in the thinner bedded horizons. Well developed aligned pseudoandalusites in the schist, poorly developed graded bedding. Minor occurrences of well bedded schist and quartzite, the couplet being approximately 1 to 1.5 m in thickness with about 33% quartzite. Exceptionally well graded. Minor occurrences of massive quartzites between 1 and 2 m in thickness with thin, 1 to 10 cm, interbeds of schist.

Dlirp Dlgg Dlirp - Israel Ridge Path Member - Dlgg - Great Gulf Member
A well bedded quartzite and schist, the couplet being approximately 20 - 100 cm in thickness and equally divided between the two lithologies. Well developed, aligned pseudoandalusites and graded beds. Rare occurrences of massive quartzites between to 1 and 2 meters in thickness with thin, 5 to 10 cm, interbeds of schist.

Dlec Dlbl Dlec - Edmonds Col Member - Dlbl - Bigelow Lawn Member
Massive schist with randomly spaced, thin quartzites approximately 1 to 5 cm in thickness. The quartzites make up approximately 5 to 10 % of the unit. Graded bedding is rare. Garnet coticules are occasionally found and pseudoandalusites are less coarse.

Dljq Dlog Dljq - John Quincy Member - Dlog - Oakes Gulf Member
A well bedded quartzite and schist, the couplet being approximately 10 - 150 cm in thickness and equally divided between the two lithologies. Well developed, aligned pseudoandalusites and graded beds. One rare occurrence of a 30 cm thick, 1.5 m long quartz pebble conglomerate horizon was found.

Dlpl Dlab Dlpl - Pine Link Member - Dlab -Abandoned Bridge Member
This member consists of massive, slightly rusty schist with thin beds of quartzite. The schist layers are commonly 1 to 1.5 m in thickness with rare occurrences of 2 m thick beds. The quartzite beds are commonly 1 to 5 cm in thickness. Pseudo-andalusites are very common in this member and both graded beds and garnet coticules are rare.

Dlojr Dlojr - Old Jackson Road Member
This member consists of layers of quartzite alternating with thinner layers of schist. The quartzite layers are up to 1 m in thickness with rare beds up to 2 m. The schist layers are commonly 15 to 50 cm in thickness. Rare graded beds are found in this member and coticules and pseudo-andalusites are not observed.

Dlnr Dlnr - New River Member
This member consists of mostly massive schist with thin quartzite beds. The quartzite beds are commonly 3 to 4 cm in thickness. Graded beds and pseudo-andalusites are not common but discontinuous 1 cm layers of garnet coticule are observed.

Dlmig Dlmig - Migmatitic Littleton Formation
A light gray migmatitic gneiss with alternating layers of quartz + feldspar and biotite-rich schist. Layering is planar to swirly. Rare, oval 20 to 100 cm long granofels clasts(?) are found. Very simliar to Src below but without rusty weathering or calc-silicate pods.

SILURIAN

Sm Sm - Madrid Formation -- The Madrid Formation is a fine-grained, thinly laminated, granofels with well-defined alternating layers of dark biotite-rich, schistose granofels and greenish-purple, calc-silicate-rich granofels. The individual layers of granofels are from 1 to 5 cm thick. No graded beds are found. The formation weathers to a dark greenish-gray and consists of actinolite, quartz, biotite, plagioclase, sphene, garnet, and trace amounts of chlorite, and epidote. Total thickness of the formation varies between 10 and 50 meters.

Ssf Ssf - Smalls Falls Formation - The Smalls Falls Formation is a well foliated schist with distinct red-brown rusty weathering. The formation has a dark gray to black fresh surface and is highly susceptible to weathering. The mineral assemblage includes muscovite, quartz, biotite, plagioclase, chlorite, sillimanite, graphite, pyrrhotite, and ilmenite. Quartzite makes up less than 5% of the unit, with layers up to 1 cm in thickness. No graded beds are found. Total thickness of the formation varies between 10 and 50 meters.

Spm Spm - Perry Mountain Formation - Dark gray schist with interbedded light gray to white quartzites that are commonly 4 to 10 cm in thickness. Quartzites make up 30 to 40 % of the unit and can range up to 60 cm in thickness. The mineral assemblage includes quartz, plagioclase, biotite, muscovite, chlorite, sericite, and trace garnet, ilmenite, tourmaline, monazite, zircon, and sillimanite. The unit is discontinuous ranging between 0 and 75 m in thickness.

Sr - Rangeley Formation - general description
The Rangeley Formation is a gray migmatitic orthogneiss with abundant calc-silicate lenses. A few beds of schist and quartzite are sometimes preserved, having escaped migmatization, and in these rare locations, rare graded bedding is found. The mineralogy of the gneisses is composed of quartz, plagioclase feldspar, biotite, muscovite, chlorite, sericite, sillimanite, garnet, ilmenite, and trace monazite, zircon, and tourmaline. The calc-silicate lenses are most often aligned parallel to schistosity planes, but some are at slight angles or, in the extreme, perpendicular to schistosity. Minerals in these lenses include quartz, actinolite, plagioclase, diopside, biotite, clinozoisite, sphene, garnet, magnetite, and trace monazite, zircon, and ilmenite. Within the gneisses are mappable zones of rusty gneiss, rusty schist, calc-silicate granofels, and amphibolite. The descriptions of the Rangeley Formation members given below focuses on the lithologic variations in the gneiss and the mappable subordinate units mentioned above. Stratigraphic order is based on the uninterrupted juxtaposition of the younger Smalls Falls, Madrid, and Littleton Formations.

Rangeley Formation Members

Src Src - Crawford Member
A migmatitic gneiss with alternating layers of white quartz + feldspar and black biotite-rich schist. Layering is planar to swirly. Angular quartz and/or feldspar segregations (clasts?) between 2 and 8 cm in diameter are common. Elongate, rectangular lenses (clasts?), .5 to 2 meters in length, of well-bedded calc-silicate granofels and ellipsoidal lenses (clasts?), 10 to 50 cm long, of concentrically mineralogically zoned calc-silicate granofels without bedding are common throughout this unit. In places the gneiss is extensively injected by two mica pegmatites, aplites, and granites.

Srcg Srcg - Granofels
Within this member are sections of fine-grained, well layered granofels with alternating layers of dark gray biotite + plagioclase schistose granofels and gray to drab purple-green, garnet + actinolite + biotite calc-silicate granofels. Bedding is discontinuous with large blocks that range between approximately 50 and 700 m in length and 10 to 30 meters in width. Lithologically similar to Sreg and Sm.

Srcr Srcr - Rusty Schist
A thin unit composed of platy schist with extreme red-brown rusty weathering. Minerals included are quartz, biotite, plagioclase, muscovite, chlorite, sericite, ilmenite, and trace amounts of monazite, zircon, graphite, and pyrrhotite. Bedding is indistinct due to the lack of quartzites. The unit is approximately 5 to 25 meters wide and has only been mapped in small belts, each approximately 500 m long. Lithologically similar to Ssf.

Sre Sre - Eisenhower Member
A moderately red brown rusty weathering, medium- to coarse-grained, migmatitic gneiss with abundant calc-silicate lense. The distinguishing feature between the Crawford and Eisenhower Members is the prominent rusty weathering that the Eisenhower Member exhibits; otherwise these members are identical.

Sreg Sreg - Granofels
Within the Eisenhower Member is a section of fine-grained, well layered granofels with alternating layers of dark gray biotite + plagioclase schistose granofels and gray to drab purple-green, garnet + actinolite + biotite calc-silicate granofels. The single section of this lithology mapped in the field area is approximately 800 m in long and 30 m wide. Lithologically similar to Srcg and Sm.

Srea Srea - Amphibolites
This is an area within the Eisenhower Member migmatite where rare blocks of amphibolite are found. The blocks are dark brown to black in color, show indistinct layering and range in size from 1 to 20 m in length. Minerals include hornblende, quartz, plagioclase, biotite, magnetite, garnet, and trace amounts of monazite, and zircon.

Sr Sr - Rangeley Formation unmigmatized
The unmigmatized Rangeley weathers rusty gray to brown and is comprised of layers of dark schist and gray quartzite of variable thicknesses. The schist layers are generally well foliated and rusty and usually 30 cm to 1 m with rare layers of 1-5 cm. The quartzite layers range in thickness from 2 to 20 cm with rare beds of over 30 cm. The average ratio of schist to quartzite bedding thicknesses is 60:40. Graded beds are observed but are rare and grading was not as defined as in the Littleton schists and quartzites. Small lenses and larger layers of calc-silicates are observed up to 1.5 m in length. Injections of pegmatite are found throughout the entire unmigmatized Rangeley Formation and make up approximately 10% to 20% of the outcrops. Also present in this member is a massive quartz pebble conglomerate approximately 30 m in thickness containing 1-2 cm clasts of quartz in a well foliated muscovite/biotite/quartz matrix.

ORDOVICIAN

Oama Oama - Ammonoosuc Volcanics - Amphibolite -
A predominantly dark-green actinolite biotite garnet amphibolite facies metavolcanic tuff. Amphibolite is interbedded with very thin (1-3 m) gray weathering, biotite, muscovite, garnet gneiss. Occasional sulfidic quartzite lenses also occur throughout the unit. The unit also contains zones of mylonite.

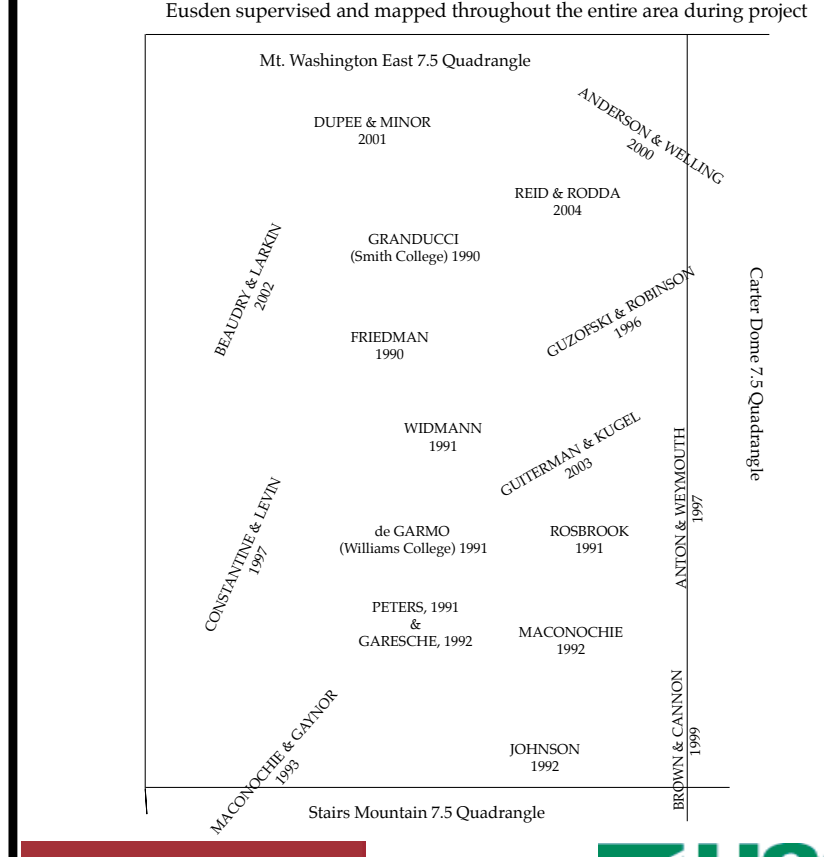
Oamg Oamg - Ammonoosuc Volcanics - Gneiss
This unit is a gray weathering, feldspathic, biotite, garnet gneiss. It is thickly to thinly interbedded (1-10 m intervals) with amphibolite and rusty gneiss and highly injected with two-mica pegmatite and granite sills.

Oamr Oamr - Ammonoosuc Volcanics - Rusty Gneiss
This unit is predominantly a regularly bedded rusty weathering, biotite, muscovite, garnet gneiss with a moderate foliation. Thin amphibolite layers ranging in thickness from .5 to 1 m are interbedded throughout.

Obqm Obqm - biotite quartz monzonite
The foliated biotite quartz monzonite is an intrusive gneiss of the Oliverian Plutonic Series. The unit mapped in this study area constitutes part of the Jefferson Gneiss Dome.

Map compilation responsibility

Bates College undergraduate students mapped individual areas during the years indicated.
Eusden supervised and mapped throughout the entire area during project



Bates College

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Acknowledgements
Thanks to the Bates College undergraduate students listed above for their hard work and dedication to the geologic mapping. Logistical support from the Randolph Mountain Club, Appalachian Mountain Club, Mt Washington Auto Road and United Sates Forest Service was much appreciated. Grant support for the project was from the National Science Foundation, Petroleum Resarch Foundation, United States Geological Survey, New Hampshire Geological Survey and Bates College. This map partially funded by USGS STATEMAP Grant #04HQAG0064.

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Geochronology -- Ages of the igneous and metamorphic rocks

400 Ma (a) -- Crystallization age in millions of years for igneous rocks. Letter in parentheses refers to reference list below

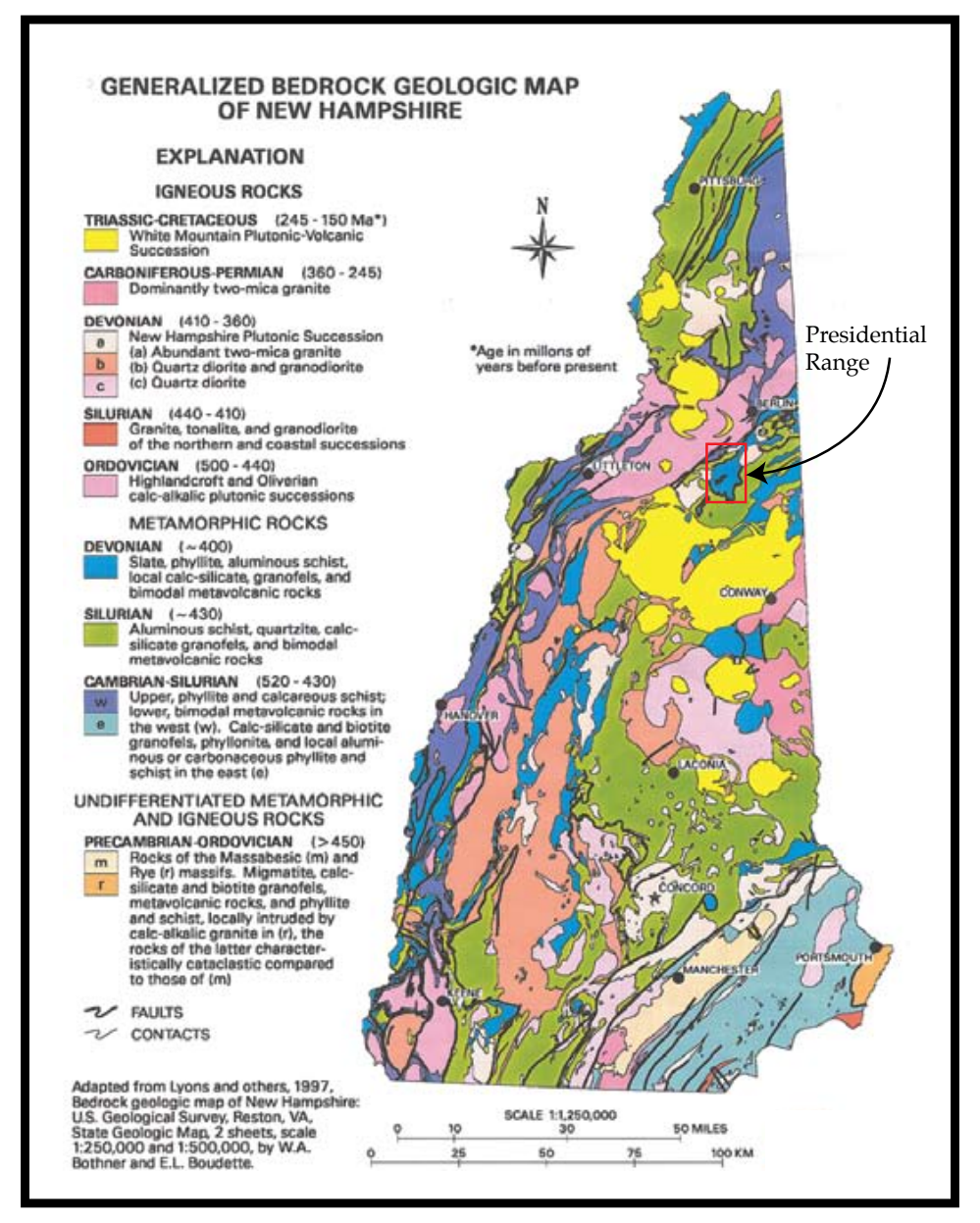
● 397 Ma (b) -- Age in millions of years for the culmination of metamorphism in the schists and gneisses. Red dot shows sample locality. Letter in parentheses refers to reference list below where more details may be examined

Reference List

(a) Eusden J. Dykstra. Jr., Guzofski, Christopher. A., Robinson, Alexander. C., and Tucker, Robert. D., 2000, Timing of the Acadian Orogeny in Northern New Hampshire, Journal of Geology, v. 108. pp. 219-232.

(b) Eusden, J. Dykstra Jr., and Anderson, Krista B., 2001, Electron microprobe age dating of monazite from the Acadian Orogeny, Presidential Range, New Hampshire: Geological Society of America Abstracts with Programs, v. 33, number 6, p. A-81.

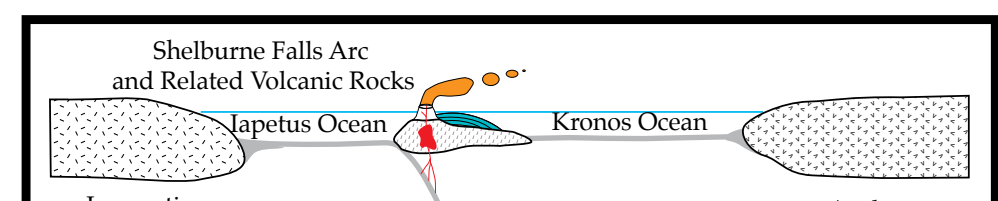
(c) Larkin, Rebecca. R., and Eusden, J. Dykstra. Jr., 2004, Electron microprobe age dating of monazite from the Bretton Woods pluton, Presidential Range, New Hampshire: Geological Society of America Abstracts with Programs, Vol. 36, No. 2, p. 152.



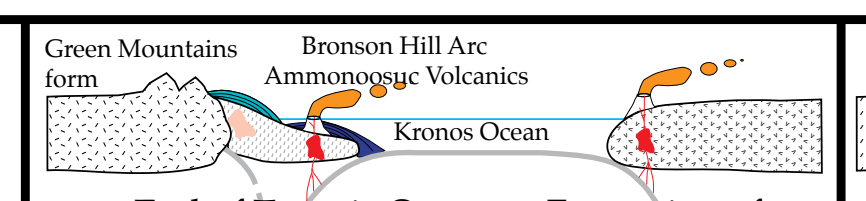
Explanation of symbols

- Geologic contact
- D0 normal fault.
- D1 fold axial trace
- D2 thrust fault. Teeth on upper plate
- D3 fold axial trace
- D4 fold axial trace
- D5 fold axial trace
- Southeast limit of Oliverian doming
- Mesozoic brittle fault with silicified zone (orange oval)
- Overturned syncline
- Overturned anticline
- Anticline
- Syncline
- Basalt dike
- \+ Exposure of granite, pegmatite and/or aplite
- 24 Strike and dip of bedding. Tops unknown
- 24 Strike and dip of bedding. Tops upright
- 24 Strike and dip of bedding. Tops inverted
- 24 Strike and dip of foliation, S1.
- ⊕ Horizontal bedding and foliation. Tops unknown
- 60 45 Joined symbols indicating two, non-parallel fabrics Strike and dip of foliation and bedding
- 60 45 Strike and dip of foliation and upright bedding
- 60 45 Strike and dip of foliation and inverted bedding
- 24 Compound symbols indicating two parallel fabrics Strike and dip of foliation and bedding
- 24 Strike and dip of foliation and upright bedding
- 24 Strike and dip of foliation and inverted bedding
- 9 Photo locality. Number refers to photo on back of map

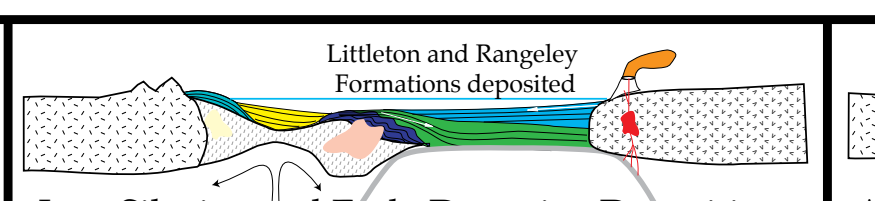
CROSS SECTIONS AND TECTONIC HISTORY, PRESIDENTIAL RANGE, NEW HAMPSHIRE



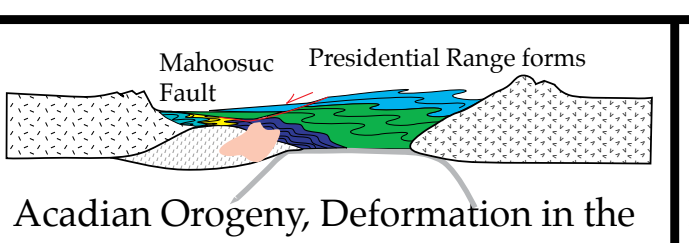
Pre-Taconic Orogeny, 470 million years ago



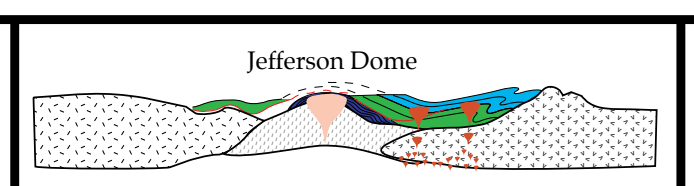
End of Taconic Orogeny, Formation of Bronson Hill Arc, 450 million years ago



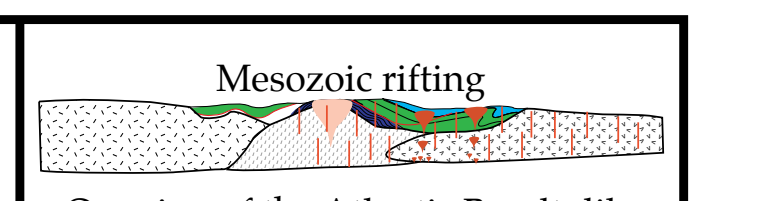
Late Silurian and Early Devonian Deposition 420 million years ago



Acadian Orogeny, Deformation in the Early Devonian, 410 million years ago



Rise of Jefferson Dome, Granites in the Carboniferous, 360 million years ago



Opening of the Atlantic,Basalt dike intrusion, 180 million years ago

The Map

The map shows the surface distribution of rock types in the Presidential Range of the White Mountains, New Hampshire. Most of the rocks are metamorphic in origin, having been recrystallized from older sedimentary and less abundant volcanic rocks, and a few are igneous, having formed by the crystallization of magma as it cooled. The forest and soil cover over the rocks are not shown so that the underlying bedrock can be inferred. Each rock type is given a name and assigned a corresponding abbreviation and a color that are keyed to the legend which also contains detailed descriptions of the age, texture, color, mineralogy and thickness of each map unit. For example, the "Sr" labeled on the map refers to the Silurian Rangeley Formation while "Oam" represents the Ordovician Ammonoosuc Volcanics. The map was created through the combined efforts of about 30 geologists from Bates College in Lewiston, Maine who investigated all outcrops of bedrock in the Presidential Range during the course of 14 field seasons. In order to find, measure and describe each rock exposure, geologists hiked all the trails in the range as well as bushwacked up or down every ravine, ridgeline, and brook. Some small rock samples were taken for microscopic analysis and for radioactive age dating to determine the age of the rocks. The abundant loose boulders were not mapped.

Symbols

There are hundreds of symbols on the map that show the strike and dip, or orientation, of planar features that have been measured in rock outcrops. These represent sedimentary bedding planes or foliation planes defined by the preferred orientation of plate-like mica minerals that formed as rocks were deformed. Each symbol represents an exposure of rock where a geologist recorded a description of the rock and used a transit to measure the orientation of these features, expressed as values of strike and dip. The direction of strike is depicted by the long line of the symbol oriented as an azimuth or bearing with respect to north. The dip is symbolized by the short line or triangle perpendicular to the strike line, labeled with a number that indicates the angle at which the plane descends into the earth. Other symbols with a "u-turn" arrow or half circle on the strike line tell whether the beds are upside-down, called "tops inverted", or right-side-up, called "tops upright", respectively. In the first instance, the rock layers were folded so that they were flipped over completely.

Faults and folds, which are large scale structures in the rocks, are also shown by a variety of line symbols explained in the legend. Both normal faults and thrust faults were mapped. In a normal fault, the block overlying the dipping fault, called the hanging wall, moves down the fault plane as it might under the influence of gravity. In a thrust fault, the hanging wall block moves up the fault plane against gravity due to compression by tectonic forces. Under some conditions, the rocks have been folded without fracturing along a fault plane. Folds that are bowed up are called anticlines, and those that are bowed down are called synclines. Some folds have been pushed over on their sides so that both limbs of the fold are nearly horizontal; these are called overturned folds. The Presidential Range has experienced six-stages of folding and faulting. Each phase is called a "deformation" and abbreviated D#, with "#" being a number that indicates the relative age of the deforming events. For example, D0 represents a phase of normal faulting and the first and oldest deformation, and D5 represents the youngest phase of fold deformation.

Cross Sections

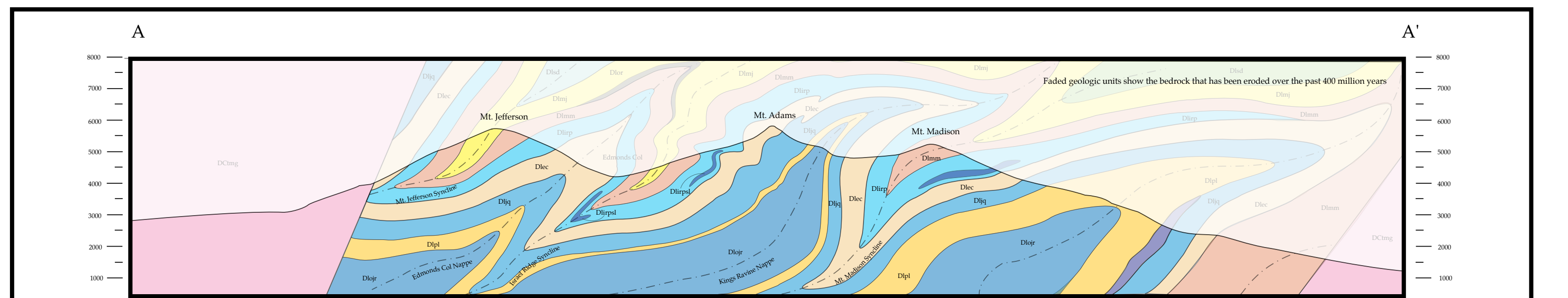
The cross sections A-A' and B-B' show the geology below the surface of the earth as well as the geology that has been eroded away from the mountain tops when viewed as an imaginary vertical slice between each pair of points on the map. The arrangement of geologic units shown on the cross sections is determined by geometrically projecting the dips of features both below and above the ground surface. Today's skyline is represented by the change from faded (the above ground eroded rocks) to solid colors (the geology below ground level).

Photos

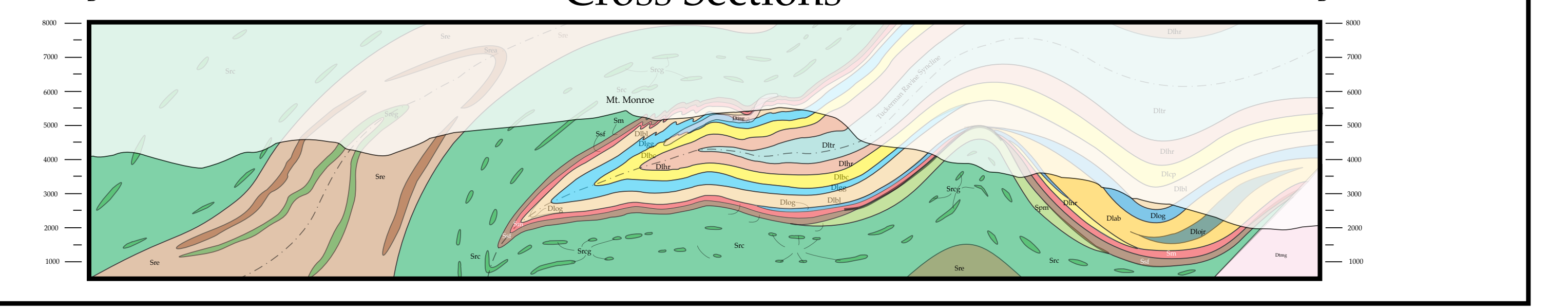
There are sixteen photographs illustrating major rock types shown on the map. Each photograph is identified by a number in a red circle that keys it to a specific locality on the map and to the description in the text below.

The Geologic History

Panels A through H below provide an overview of the geologic history of the Presidential Range. The history begins about 450 million years ago during the Ordovician time period (Panel A). The oldest rocks presently exposed in the high peaks in the Presidential Range were deposited millions of years later, during the Silurian and Devonian time periods, approximately 430 to 410 million years ago (Panels B-D). The main phase of plate tectonic collision in the Presidential Range occurred about 400 million years ago in the Devonian time period (Panels E and F). The mountain building period lasted about 40 million years, ending approximately 360 million years ago in the Carboniferous period (Panel G). There are no rocks from the Permian period, only a few scattered basalt dikes from the Triassic and Jurassic periods (Panel H) and no rocks from either the Cretaceous or Tertiary periods. The history ends with the Quaternary glaciations (Panel H), but slow erosion and human impacts continue to this day.



Cross Sections



A

Oliverian Domes and Ammonoosuc Volcanics

The oldest rocks in the area are found in the northwest corner of the map. They consist of a biotite quartz monzonite of the Oliverian Plutonic Series (Obqm) and part of the Jefferson Gneiss Dome. These are mantled by the next youngest rocks, Oama, Oamg and Omar on the map or, collectively, the Ammonoosuc Volcanics. This is a mix of generally dark basaltic rocks with lighter fragments of what used to be rhyolite (Photo 1). The Oliverian and Ammonoosuc rocks are part of a 450 million year old volcanic island arc that collided with what is now Vermont to form the Green Mountains during an earlier mountain building event called the Taconic Orogeny. At this point in time none of the other rocks shown on the map existed. Metamorphism by the intense heat and pressure resulting from this and later collisions changed the volcanics into amphibolites; rocks rich in the black needle-like mineral amphibole. The Obqm gneiss was originally a lower density rock buried by more dense Oam volcanics. This created an unstable situation with lighter rocks underlying heavier rocks. During later plate collisions, the Obqm rose up through the Oam and younger rocks as a flowing solid to make the broad Jefferson Dome, creating a more stable rock mass. In the northwest corner of the map there is a dashed red line marking the southeast limit of this doming. Northwest of this line, the rocks all dip towards the southeast, having been tilted by doming. Southeast of the line, the rocks dip generally westerly and were not tilted by the doming.

B

Silurian Rangeley Formation

The sedimentary rock history begins with deposition of the Rangeley Formation (Sr). This rock was deposited in the Early Silurian period, 430 million years ago, in a deep marine basin immediately east of the Ammonoosuc volcanic arc.

The Rangeley Formation is largely a gneiss and has been extensively metamorphosed up to the point where it actually started to melt in places. Photo 2 shows a typical outcrop where the lighter quartz and feldspar rich layers are the now solidified, once melted, parts.

The Rangeley gneisses also have blocks of different rock types embedded in them, ranging in size from centimeters (Photo 3) to meters (Photo 4). These formed by a combination of processes. First, there were earthquakes in this active tectonic setting that caused submarine landslides along normal faults; the Mahoosuc, Graham Trail and Pinkham Notch normal faults shown on the map. These seismic events broke up the Rangeley Formation into a disaggregated mix of blocks surrounded by a muddy matrix. Secondly, as the Rangeley was metamorphosed and underwent partial melting; fluids and magma moved through the rock, further breaking it up into what we see in the Presidential Range today.

Some of the blocks are big enough to show on the map (for example, Srcg, Srcr, Sreg and Srea) and have been found on the flanks of Mts. Monroe, Eisenhower and Clay, as well as down in the Rte. 16 Pinkham Notch valley at Emerald Pool.

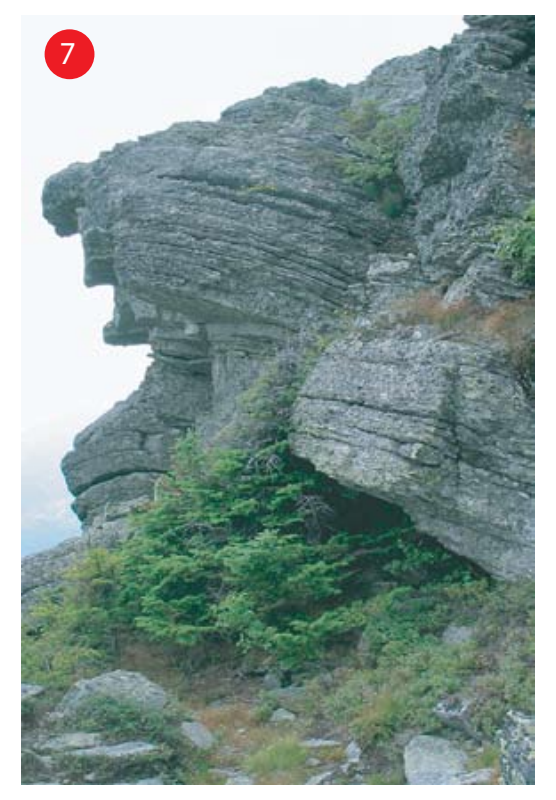
C

Perry Mountain, Smalls Falls and Madrid Formations

After deposition of the Rangeley Formation and throughout the remainder of the Silurian time period (to 410 million years ago), the Perry Mountain, Smalls Falls, and Madrid Formations were laid down in the ancient ocean basin. Each of these formations is quite thin, often discontinuous and composed of unique white quartzites (Spm), rusty schists (Ssf) and gray-green calc-silicate granofels (Sm) (Photo 5). The depositional setting for these formations is envisioned as a shrinking marine basin in which the geochemical environment became progressively more reducing as it was closed off to oxygen supply. Subsequently the basin became a more open, oxygenated basin with good circulation. The Smalls Falls Formation is now very rusty-weathering and brown in color, suggesting it was oxygen-starved as a marine sediment. These characteristics are the result of the weathering of iron-bearing sulfide minerals like pyrite or pyrrohtite, where the iron is in the reduced chemical form. Atmospheric oxygen attacks these minerals rendering the sulfides into iron oxide minerals like hematite. The Madrid Formation is purple and greenish in color with a good deal of carbonate. A carbonate reef composed of limestone probably served as a sedimentary source for the Madrid Formation. This sedimentary environment is likely given that at the time of deposition these rocks were in warm equatorial waters. This change from oxygen-starved ocean basin to more open basin was caused by global plate interactions where some barrier to circulation opened up relatively quickly. These formations are quite distinctive in appearance but generally very difficult to find. The best places to see them are near Lakes of the Clouds, on Boott Spur, the base of the Lower Headwall at Tuckerman Ravine and, especially, along the West Branch of the Peabody River in Great Gulf just above Long Island Rapids.

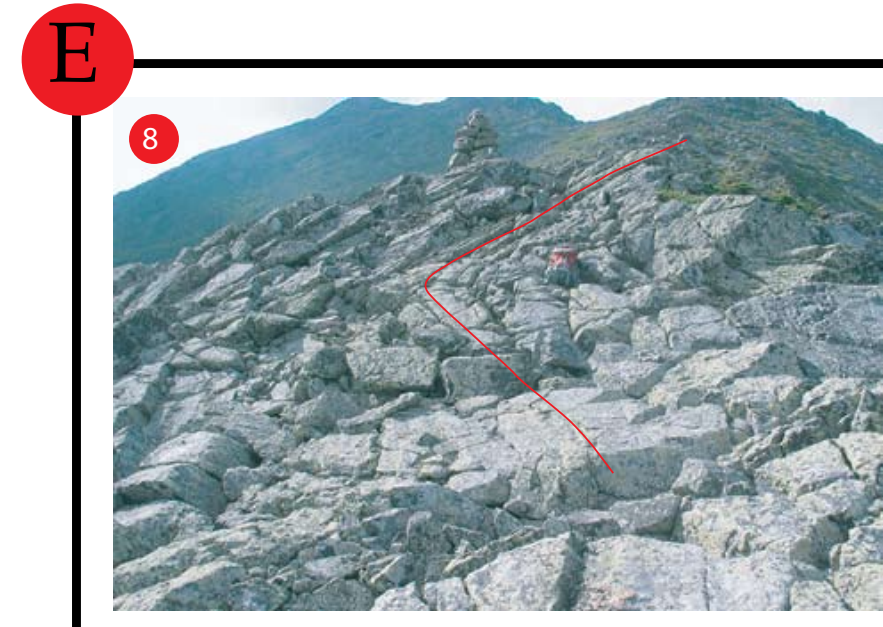
D

Devonian Littleton Formation



The Littleton Formation was then deposited atop these older rocks in the Early Devonian period, 409 million years ago, and was derived from the Avalon plate to the east. This sedimentation episode heralded the onset of the Acadian plate collision that built the framework for today's Presidential Range. The Littleton Formation is made up of different combinations of what were once mud and sand deposited in a deep marine setting. These sediments were metamorphosed during the Acadian collision and are now schists and quartzites, respectively. On the map, units shown in various shades of yellow, such as Dlmj, Dlcp and Dlab, are schist-rich with only 10-20% quartzite (Photo 12 below). Units that are blue, such as Dlog, Dlag, Dlirp and Dlgg, are quartzite-rich with less than 50% schist (Photo 6). The orange-colored units, such as Dlmm and Dlhr, have roughly equal amounts of schist and quartzite layers interbedded on the centimeter scale (Photo 7). These rocks were deposited as a series of overlapping submarine fans on the slope of the marine basin. As the name indicates, these features have a fan-like shape and the sediment would move from the "handle" of the fan down toward its outer edge, spreading out over the whole area. Each fan had a feeder channel that was primarily filled with sands and extend downslope from the "handle". Sediments became progressively more mud-rich with increasing distance away from the channels towards the edge of the fan. Massive schists formed from these muds, like the Parapet near Star lake or in Edmonds Col (Dlec), were probably the distal (or outermost) edges of one such fan. The thin, evenly bedded muds and sands (schists and quartzites) exposed on Mt. Madison (Photo 7, Dlmm) and throughout Bigelow Lawn (Dlbl) were probably the mid section of a fan. The thick sands (quartzites) exposed on the shoulder of Sam Adams just above Storm Lake (Dlirp), along Osgood Ridge, and also just above the Alpine Garden (Dlag) on the Mt Washington summit cone were probably the feeder channel to various fans. In these fans, muds or schists dominate, the muds interbedded with the sands (schists and quartzites) are the next most common, and the sands (quartzites) are quite rare. The exact number and locations of fans that made up the Littleton Formation are unknown in part because of the complex deformation and by the lack of complete exposure. The estimated total thickness of the entire Rangeley, Perry Mountain, Smalls Falls, Madrid and Littleton Formations is 3.5 kilometers (greater then two miles), but possibly much more as neither the base of the Rangeley nor the top of the Littleton Formations has been identified.

E



Deformation of the rocks

The Acadian collision began after the Littleton Formation was deposited in front of the advancing Avalon plate. There were six pulses of deformation. Some happened before, some during, and some at the end of this collision. Geologic features associated with this deformation are labeled as D0, D1, D2, D3, D4, or D5, respectively, where symbolized on the map. D0 deformation is characterized by normal faults that predated the main collision. The Mahoosuc, Graham Trail, Moose River and Pinkham Notch normal faults formed during this time and represent earthquake-triggered slumps on the seafloor after deposition of the Rangeley and before or during deposition of the Littleton sedimentary rocks. The intervening Perry Mountain, Smalls Falls and Madrid Formations were completely or partially cut out by the faulting. On the map, the truncation caused by the Graham Trail fault is seen on the Glen Boulder Trail below the actual boulder.

D1 deformation is characterized by folds in the rock that formed 10 to 15 kilometers below the Earth's surface around 408 million year ago. At that depth, the rocks were warm, malleable and ductile, so that they "crumpled" in response to squeezing by plate collisions rather that fracturing along faults. The overall geometry of folds can be described by two measures: the distance from one limb to another (the wavelength) and the distance or height from the trough to the peak (the amplitude). In the case of the D1 folds, wavelength is on the order of 1 kilometer and amplitude is about 2 kilometers. This is illustrated by the cross sections, and in particular by section A-A' through the northern Presidential Range where three giant folds pointing east have been mapped. Each fold has a long right-side-up limb that gives way to a sharp hinge which in turn transitions into a shorter upside-down limb. Photos 8 and 9 show a couple of D1 fold hinges on Osgood Ridge and along the Auto Road, respectively. On the map, regions of upside-down (inverted) limbs are symbolized by "u-turn" dip arrows on the strike lines; conversely, regions of right-side-up (upright) limbs are symbolized by half circles on the strike lines. The best place to see examples of these features is below the summit of Mt. Washington along Chandler Ridge parallel to the Auto Road. The very top of Mt Washington is composed of upside-down Littleton Formation. The rocks remain in this orientation until the Cow Pasture where the first of two giant fold hinges is seen. From there down to Cragway Springs the rocks are all right-side-up. Further down the mountain, the second giant fold hinge is exposed near the Halfway House site. From there the rocks go through one more upside-down to right-side-up transition so that along Rte 16 in Pinkham Notch the orientation is right-side-up again.

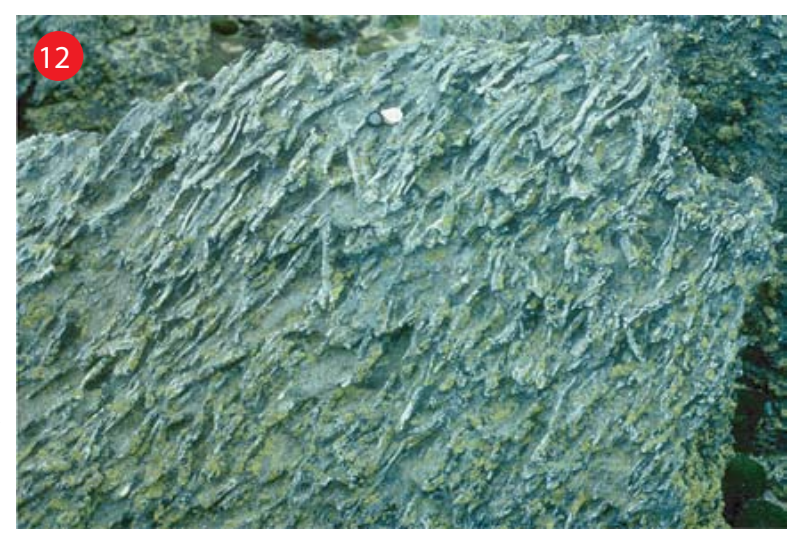
D2 deformation is characterized by the Greenough Springs Fault, which is seen in the center of the map. An abrupt break between the folded Littleton and Rangeley formations occurs along the fault where D1 folds and the Madrid, Smalls Falls and Perry Mountain formations are all cut out and missing. The fault also marks a sharp transition in the degree of metamorphism, with the Rangeley Formation having been partially melted on one side of the fault, while the Littleton Formation, on the other side, was not melted as much. This is evidence that D2 faulting must postdate the partial melting and also be younger than the D0 normal faults. The Greenough Springs Fault formed as a thrust during the Acadian collision, but after the D1 folds. During thrusting, older, deeper and hotter Rangeley Formation was brought up over the younger, shallower and cooler Littleton Formation. The Snyder Brook Fault is another D2 fault formed in the same manner.

D3, D4 and D5, the last three deformations related to the Acadian collision, were a succession of fold events that marked the final compression recorded by the rocks. Evidence of D3 and D5 is not widespread and only found in the Great Gulf and Pinkham Notch regions, respectively. D3 folds are shown with a dash–2 dots line pattern folding the Greenough Springs thrust. D5 folds are identified by a solid line pattern and are seen near the base of the Auto Road. D4 folding occurs throughout the Presidential Range and is observed on the centimeter to meter scale. Some of the best places to see the folds include the Cragway Springs hairpin corner on the Auto Road (Photo 10) and the south side of the Mt. John Quincy Adams (Photo 11). A few D4 folds are big with wavelengths on the order of 1 to 3 kilometers. One of these is found along Chandler Ridge near Nelson Crag where there is a dome like an upside-down bowl. Adjacent to it, near the three mile mark of the Auto Road, is a matching basin, a right-side-up bowl. These folds are also seen on cross section B-B' where the D1 Tuckerman Ravine fold is refolded by D4 folds.

The D0 normal faults, D1 giant folds, D2 Greenough Springs fault and D3, D4 and D5 late folds collectively record about 40 million years of predominately ductile rock deformation during the Acadian collision. This highly significant event in the geologic history of the Presidential Range started about 408 million years ago and ended 360 million years ago with the intrusion of granites that cross cut all the folds and faults.

F

Metamorphism



During the Acadian collision, metamorphism occurred simultaneously with the deformation. The muds of the Littleton Formation were transformed into shales, slates and finally schists (Photo 6) composed of new minerals. The sands changed into quartzites (Photo 12) but with little change to the overall rock mineralogy. The new minerals in the schists literally grew, at geologic rates, during metamorphism. Some of the common minerals that formed include thin, plate-like micas, both black biotite and clear muscovite, ruby red garnet, and black tourmaline. Amber-brown, rectangular staurolite, pale-pink pencil-like andalusite, and fibrous, white sillimanite are some of the less well-known but nonetheless important minerals that grew.

Metamorphism occurred in a series of pulses, much like the episodic history of deformation described above. Some metamorphic events were extensive and some localized. The earliest metamorphism occurred during the D1 folding and is characterized by the mineral andalusite. It forms the knobby, lumpy, centimeter or larger sized bumps that give the Littleton Formation schists their characteristic rough texture and fabric. Because crystal growth occurred during D1 deformation, andalusite often appears as aligned cylinders up to 10 cm in length (Photo 12). Sillimanite formed next through recrysallization of andalusite and looks like tiny bundles of microscopic, stiff, clear-to-white hair found within andaulsite. This transformation happened during the partial melting that affected the Rangeley Formation during the end of D1 folding. The green unit Src on the map shows the extent of the partially melted rock called a migmatite (Photo 2 above). Muscovite formed many times during the metamorphism, both during and after D1 folding, but always before D4 and D5 deformation. Photo 13 shows the whole process as recorded in one crystal of andalusite. The rectangular 4 inch long mineral in the middle of the photo is the former andalusite crystal. White sillimanite that has completely replaced the andalusite is clearly visible in its center. Surrounding the sillimanite is a rim of muscovite that replaced most, but not all, of the sillimanite.

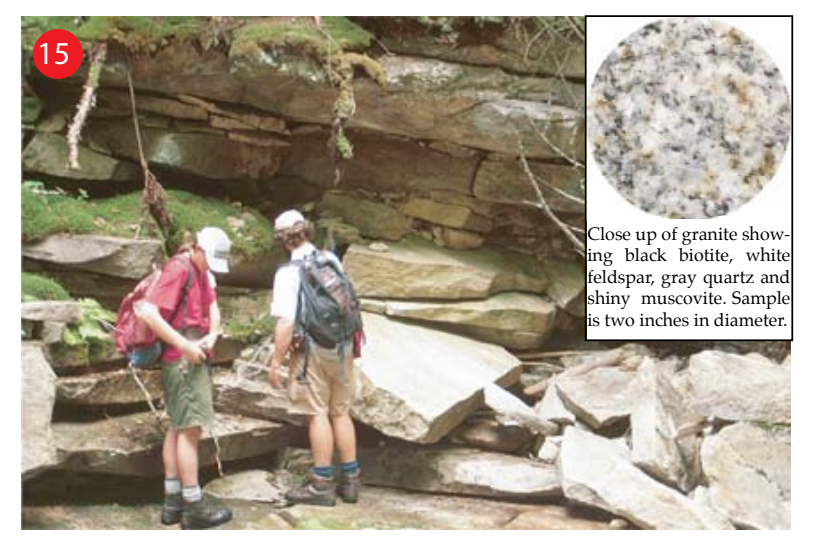
The conditions of temperature and pressure that the rocks in the Presidential Range were exposed to during the Acadian collision can be determined by the minerals that formed during metamorphism. The occurrence of staurolite, andalusite and sillimanite in the schists means that temperatures and pressures reached as high as 500-600°C and 3,000-4,000 atmospheres, respectively. This represents a dramatic change from the conditions that existed when the original sediments were muds on the ocean bottom (25°C and 1 atmosphere). The increase in pressure resulted from burial by a mountain-sized stack of D1 folds and D2 fault slices as these sediments were caught in the collision between the Avalon and ancestral North American plates. The increase in heat resulted from a steady rise in temperature as the rocks were deeply buried. Heat also came from molten rock magma and superheated geothermal fluids within the Acadian collision zone.

In order to be subjected to a pressure of 3,000-4,000 atm, the rocks of the Presidential Range would have had to be buried under an additional rock mass that was 10-15 kilometers (or 6-9 miles) thick. This great thickness of overlying rock has long since weathered and eroded away over the last 360 million years. The products of this erosion exist today as deposits of sediment on the Atlantic continental shelf and slope. The Presidential Range was much taller during the Acadian collision then it is now. If the 10-15 kilometers of eroded rock were put back on the mountains and allowed to settle by depressing the Earth's fluid-like mantle, the elevation of the ancient Presidential Range was likely in the range of 15,000 feet, as tall as the Rockies, but not as tall as the Himalayas.

Snow-white, quartz lenses seen in places like Edmonds Col (Photo 14) and Star Lake are another product of metamorphism in the Presidential Range. These are too small to show on the map but are quite visible to the eye as they are so bright and white. During metamorphism, these lenses formed from fluids squeezed and heated out of the rocks in a dehydration process. The fluids were composed of water, dissolved silica, fluorine, boron, and carbon dioxide. As they percolated through the rocks, most of these fluids escaped to the Earth's surface and became part of the atmosphere, but some, especially the most silica-rich, cooled to a solid during their passage upward through the Littleton Formation schists. These frozen fluids are the quartz lenses seen today. Quartz is one of the minerals that are most resistant to weathering. As a result, glacial striations, scratches left by the continental ice sheet a mere 18,000 years ago, are well preserved in these white rock outcrops.

G

Granites



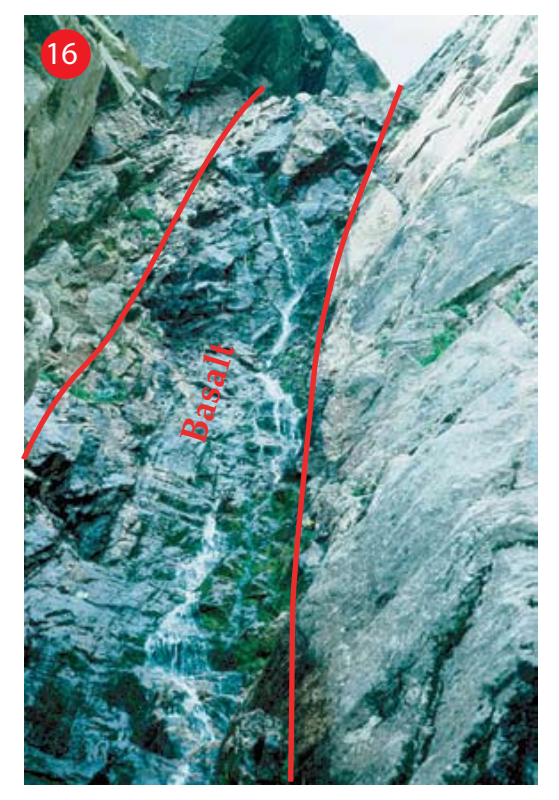
Close up of granite showing black biotite, white feldspar, gray quartz and shiny muscovite. Sample is two inches in diameter.

There are only a small number of granites exposed in this part of the Granite State. During the metamorphism, preexisting rocks partially melted and formed migmatites. Enough molten rock pooled and accumulated to produce granites. Two of the largest granites of this type are exposed at Wildcat ski area and in Bigelow Lawn. Both have been dated at 401 and 399 million years old, respectively, synchronous with the intense metamorphism during the Acadian collision. There are also dozens of smaller granite bodies that occur as pods between 5 and 100 meters in length within the metamorphic rocks. Many of these are very coarse-grained, some with crystals up to several centimeters in length. One such pod is exposed along the summit of Mt. Monroe, another near Slide Peak, and others along Cold Brook near the town of Randolph.

There are three granites found in the lower elevations of the Presidential Range. These have been named the Peabody River, Bickford and Bretton Woods granites. They all look very similar to each other and are white, small in grain size, and composed of the minerals quartz, feldspar, muscovite and biotite. Photo 15 shows a typical granite exposure at Coldspur ledges on Cold Brook, part of the Bickford granite. All three granites have been dated using radioactive methods and their ages cluster around 360 million years ago. This dates them as being a full 40 million years younger than the metamorphism and deformation described above. The likely cause of this period of igneous intrusion was collapse of the ancestral Presidential Range after the tectonic stresses ceased. Once the stress that built a mountain range and kept it uplifted ceases, the mountains will sag and decrease in elevation. As the mountaintops drop, the base of the Earth's crust rises up and heat from the underlying mantle causes the base of the crust to melt. This generates great volumes of new magma that rise up into the upper crust and cool to form granites. These young granites cut across all the metamorphic rocks and the D1 folds and D2 faults. They are probably related to the late D5 and D4 folds and may have created the folds when the magma pushed its way up through the rocks.

H

Basalts



Following the deformation, metamorphism and granite intrusion of the protracted Acadian collision, extensive brittle deformation occurred as the supercontinent Pangea began to split apart. This rifting created the Atlantic Ocean and caused abundant fractures or cracks to form in all of the rocks throughout New England. This took place in the Triassic-Jurassic periods about 180 million years ago. There are cracks of this age on every rock face in the Presidential Range. The best places to see them are in the steep faces of the headwalls of King, Huntington and Tuckerman ravines. Look for vertical and horizontal cracks extending several meters in length along these rock faces. As these cracks formed, magma from the Earth's mantle intruded along them, injecting basalt dikes into the old metamorphic rocks and igneous granites. Photo 16 shows a typical cross-cutting basalt dike occupying a crack in Pinnacle Gully, part of the Huntington Ravine headwall. There are many of these shown as thin red lines on the map and probably many more exist within the map area but are buried by the forest and soil cover.

Glaciers

The last geologic event to shape the Presidential Range was a succession of glaciations that occurred in the Quaternary period. The most recent glaciation culminated about 20,000 years ago as an ice sheet from Canada overrode Mt Washington and advanced as far south as Cape Cod, Massachusetts. It left scattered deposits in the Presidential Range notches as well as characteristic erosional landforms in the mountains, such as the glacial cirques of King, Huntington and Tuckerman Ravines. Though the glaciers were an impressive erosional force modifying the existing landscape, they did not build the Presidential Range. As the rocks portrayed on the geologic map reveal, all of the mountain building occurred 400 to 360 million years ago during the Acadian plate collision.